Heavy resonances at hadron colliders

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Snowmass 2021, EF09

Outline

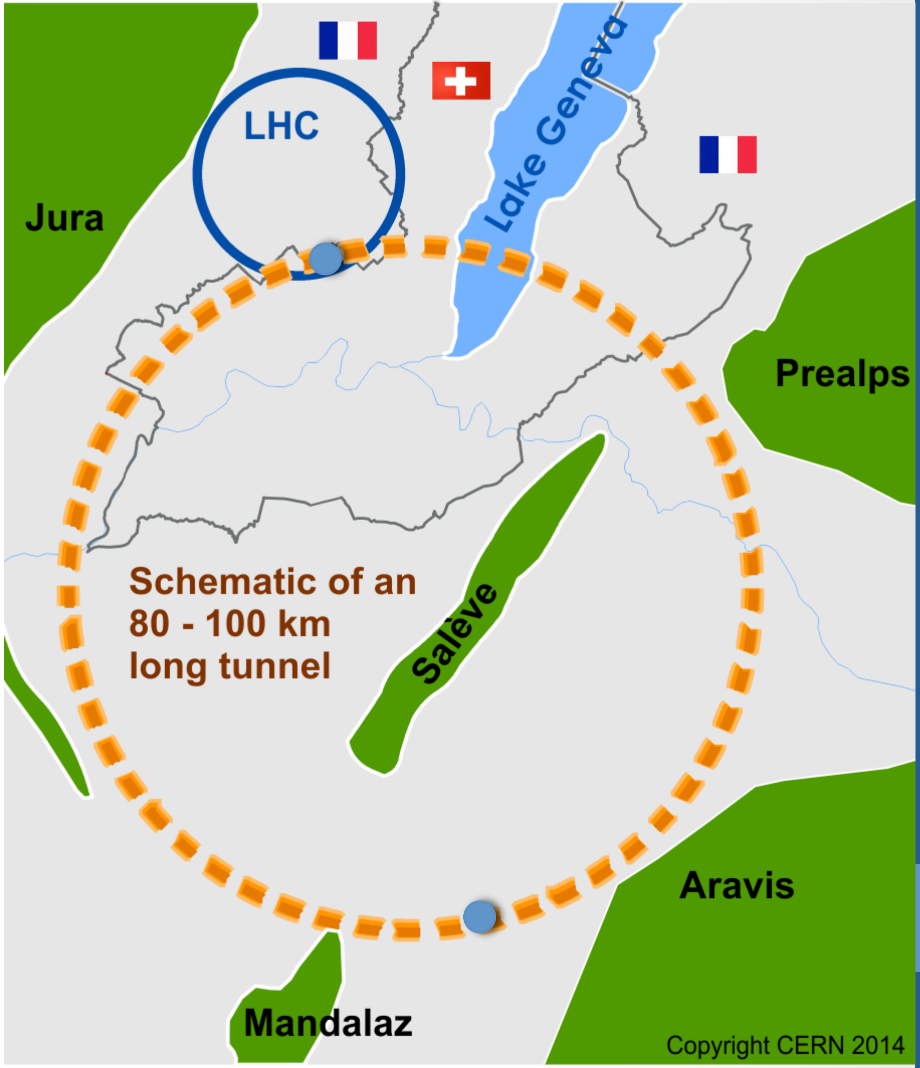
1. Frontier Hadron colliders
2. Review of the studies
3. Perspectives for future work
4. Full Simulation
5. The FCC-hh framework
6. Outlook

1. Frontier Hadron Colliders

FCC-hh @CERN

Most ambitous

- Need a new 100km tunnel
- Need 16 Telsa magnet to reach 100TeV in 100km
- Baseline Luminosity (10y)
  - 5 10^{34} cm^{-2} s^{-1} (HL-LHC) $<\mu>200$
- Ultimate luminosity (15y)
  - 30 10^{34} cm^{-2} s^{-1} $<\mu>1000$
- 2.4MW sync rad/ring x300 HL-LHC
- Considering 30ab^{-1} for the study



Environment and detector requirements

<u>@100TeV FCC-hh</u>

- The radiation level increase mostly driven by the jump in instantaneous luminosity
  - pp cross-section from 14 to 100TeV only grows by a factor 2
  - 10 times more fluence compared with HL-LHC (x100 wrt to LHC)
  - Need radiation hard detectors

- More forward physics -> larger acceptance
  - Precision momentum spectroscopy and energy measurements up to $|\eta|<4$
  - Tracking and calorimetry up to $|\eta|<6$ (at 10cm of beam line at 18m of IP)

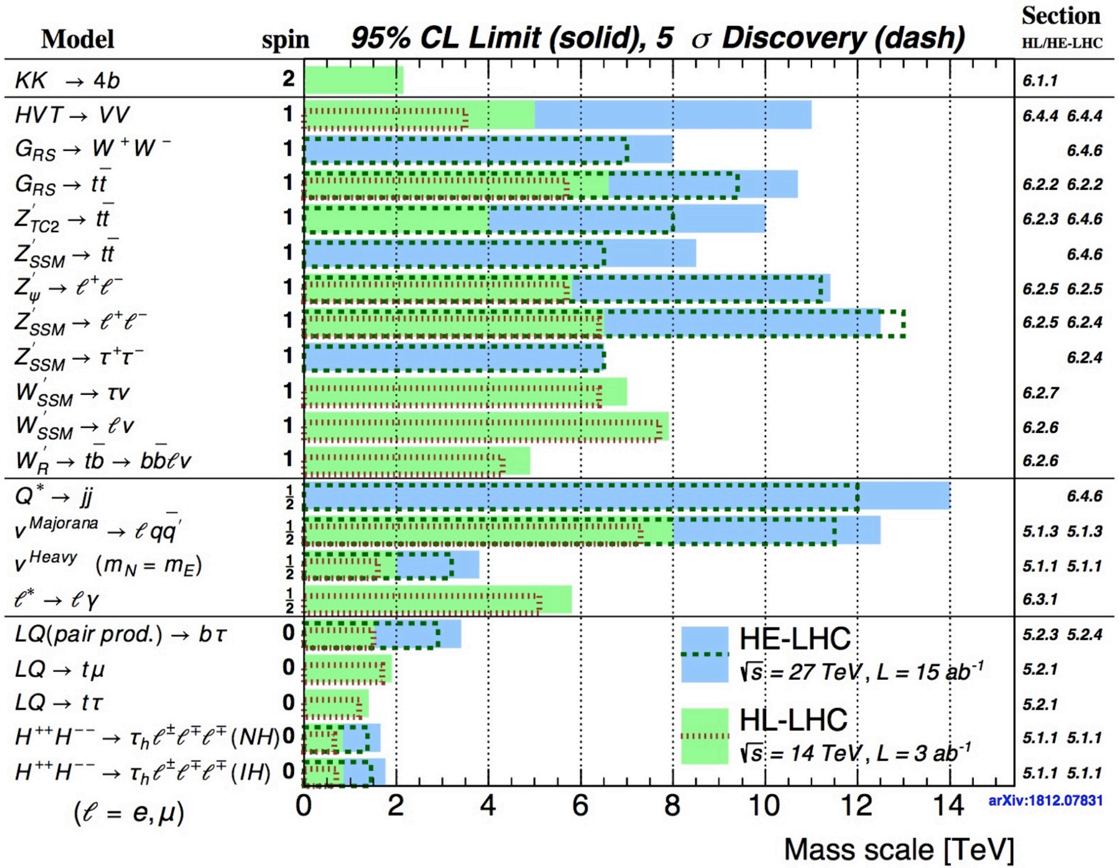
- More energetic particles
  - colored hadronic resonances up to 40TeV -> Full containment of jets up to 20TeV
  - Resonances decaying to boosted objects (top, bosons) -> need very high granularity to resolve such sub-structure

2. Review of the Studies

HL-LHC

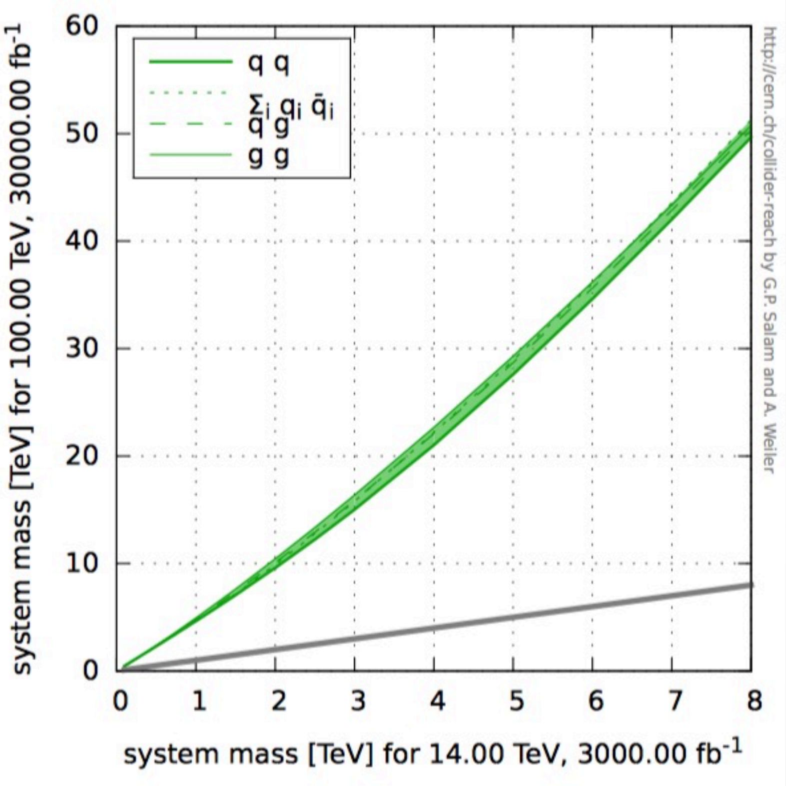
BSM HL-HE/LHC Yellow Report [1812.07831](https://arxiv.org/abs/1812.07831)

- Still some possibilities to observe a new heavy resonance at the end of HL-LHC but by no means it will be possible to study its nature
- For HR, the higher sqrt(s) the better, but remember we do not have evidence that NP lies within FCC-hh reach (could be 200-300TeV?)



Direct discovery reach at 100TeV

- To first approximation
  - The discovery reach at the highest masses is driven by the energy increase wrt to LHC
  - For √s=100TeV we expect the reach to be extended by factors 5-7 wrt LHC for the same BSM parameters



FCC-hh: Motivation

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FCC-CDR Vol. 1,3,4

- Goal of the study
  - Discovery reach for heavy objects
  - Find ways to discriminate QCD, top and boson jets by only considering hadronic decays
  - Being validated with calorimeter and tracker performances in full simulation

- No pileup assumed
  - For such heavy object the effect is hopefully not large
  - Effect on jet reconstruction and performance being studied in full simulation

- In this talk
  - Not discussing yet the physic models
  - Neither designing fully state of the art analyses
  - But rather study the performance of the FCC-hh detector

$Z' \to l^+l^-$

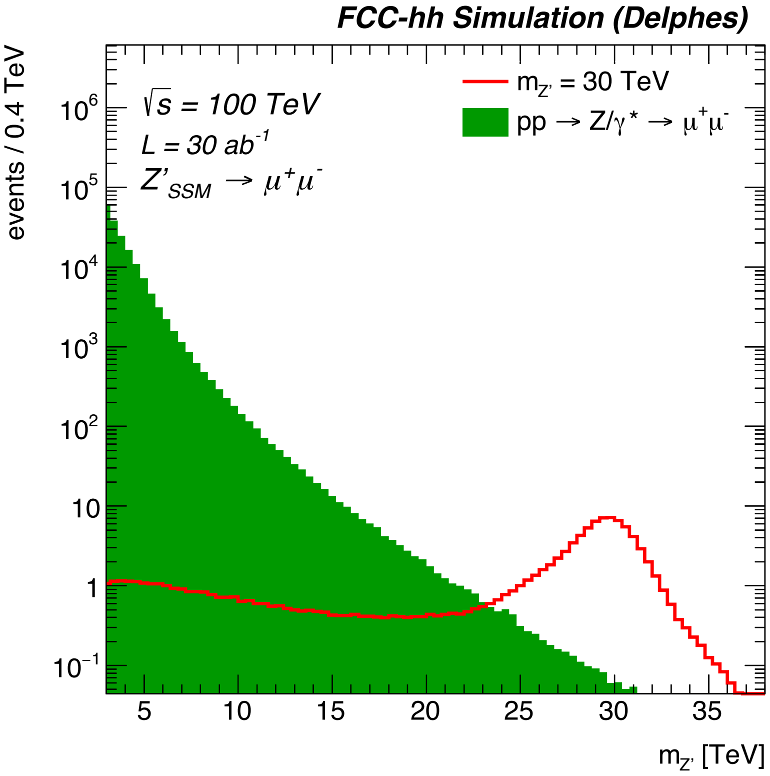
$Z' \to \mu^+\mu^-/e^+e^-$

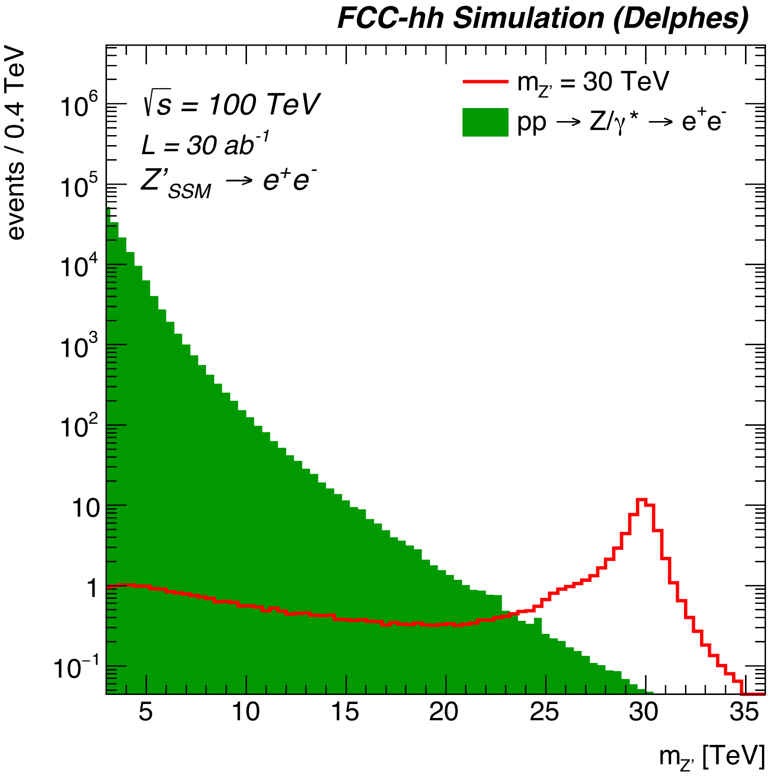
- Z' model
  - Simple benchmarks used to check detector performance
  - Allowed to tune the muon momentum resolution to 20%@10TeV

- Analysis selection
  - $p_T(\text{lepton}_1)$ and $p_T(\text{lepton}_2) > 1$TeV
  - $|\eta_{\text{lepton1}}|$ and $|\eta_{\text{lepton2}}| < 4$
  - M_{ll}>2.5 TeV (to bridge with HL-LHC reach of 6 TeV, start signal at 5 TeV)

- Uncertainties
  - 50% uncertainty on the Drell-Yan normalization

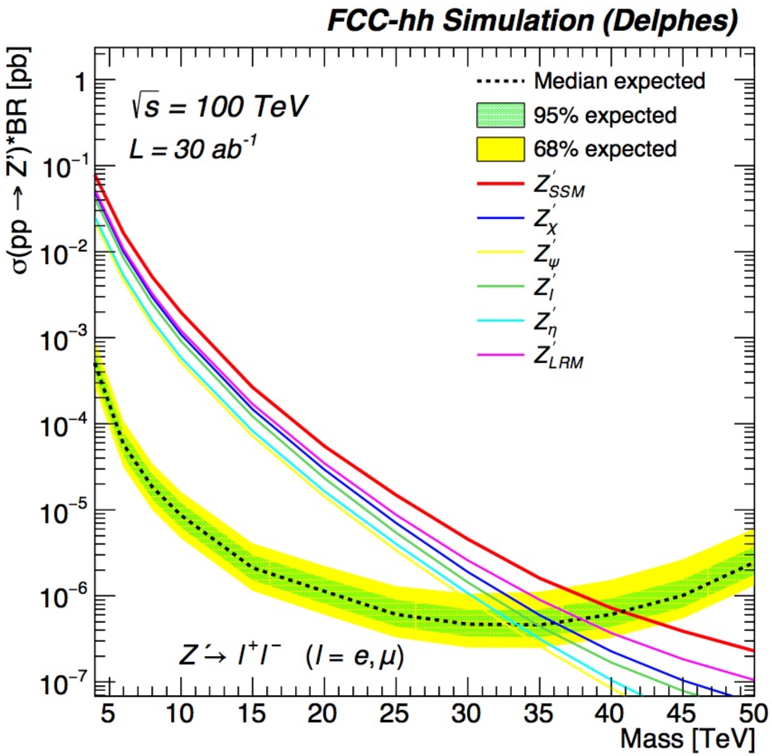
Z'->$\mu^+\mu^-$/e^+e^- (30TeV)

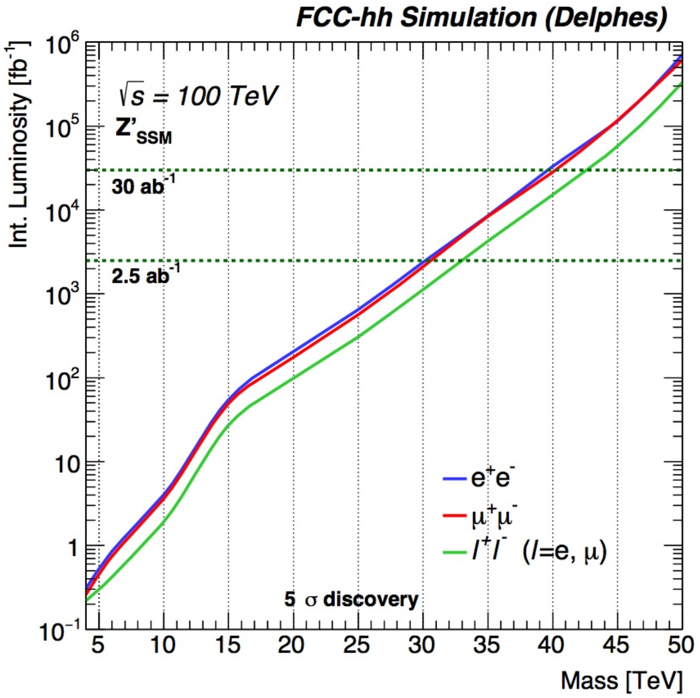




As expected better mass resolution for electrons

Limits and discovery





Reach up to 40TeV this very simple case!

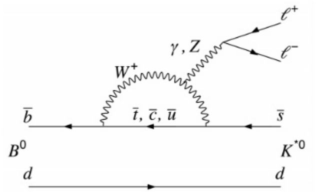
Considering 2.2fb^{-1} per day for baseline

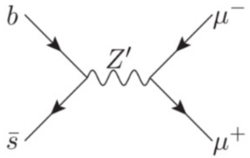
5σ discovery for:

- 20TeV after ~50 days (first year?)
- 33TeV after 10 years @ baseline
- 42TeV after full operation 25 years

Z’ flavour anomaly

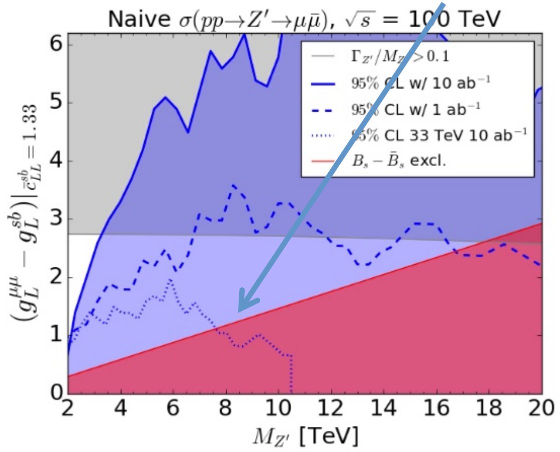
Quick interpretation of Z’->μμ

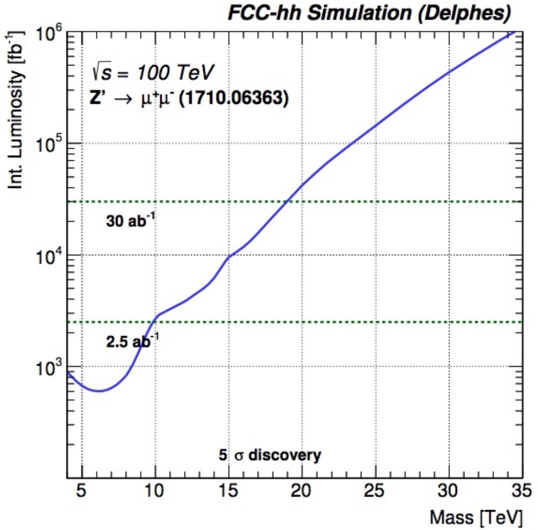


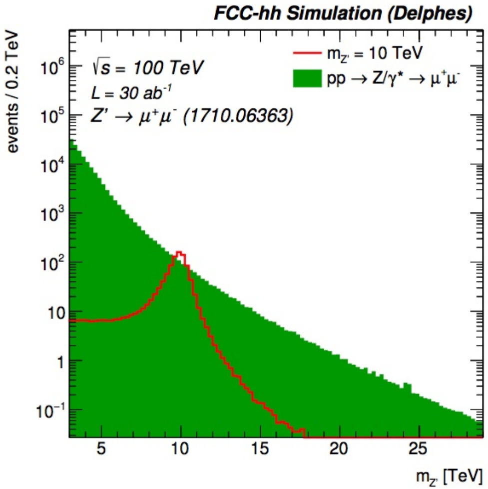


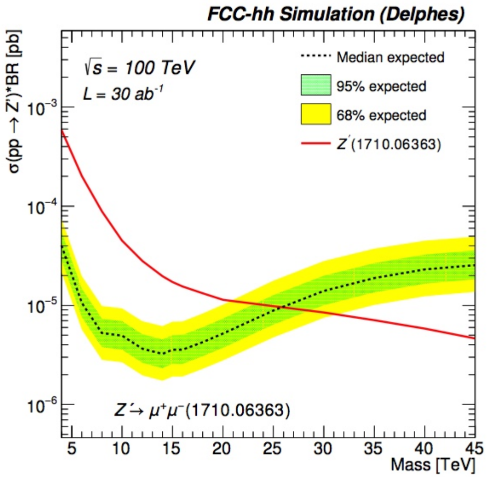
Arxiv:1710.06363

We test this line







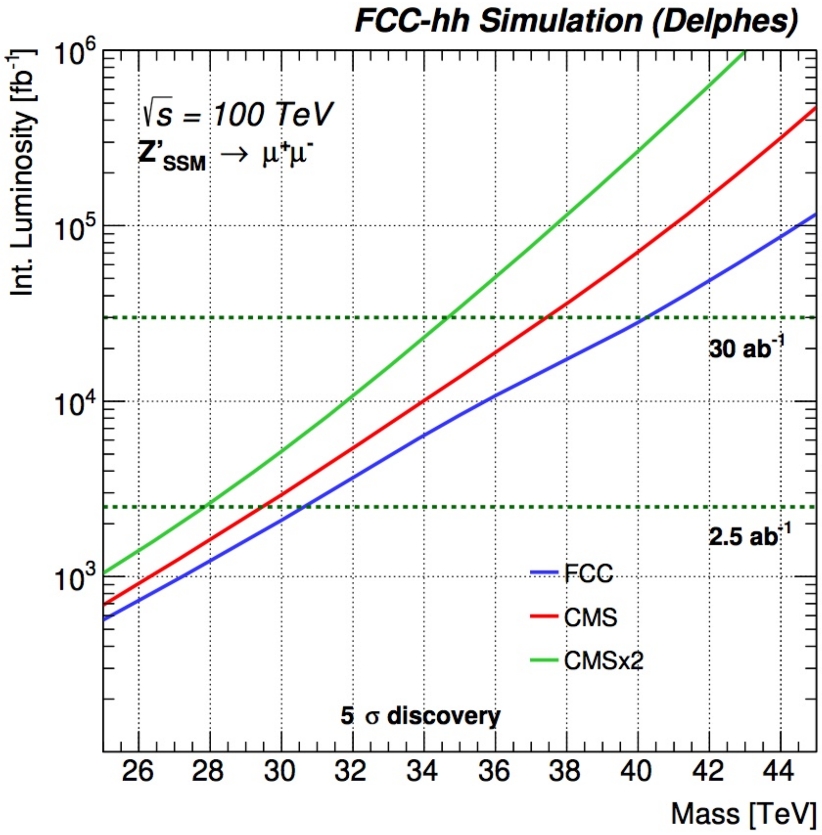


Discovery μμ degraded

Best sensitivity achieved with an assumed $\sigma_p/p \approx 5\%$ at p_T = 20 TeV corresponding to our target for the FCC-hh detector

Worse results for projected CMS resolution of $\sigma_p/p \approx 40\%$.

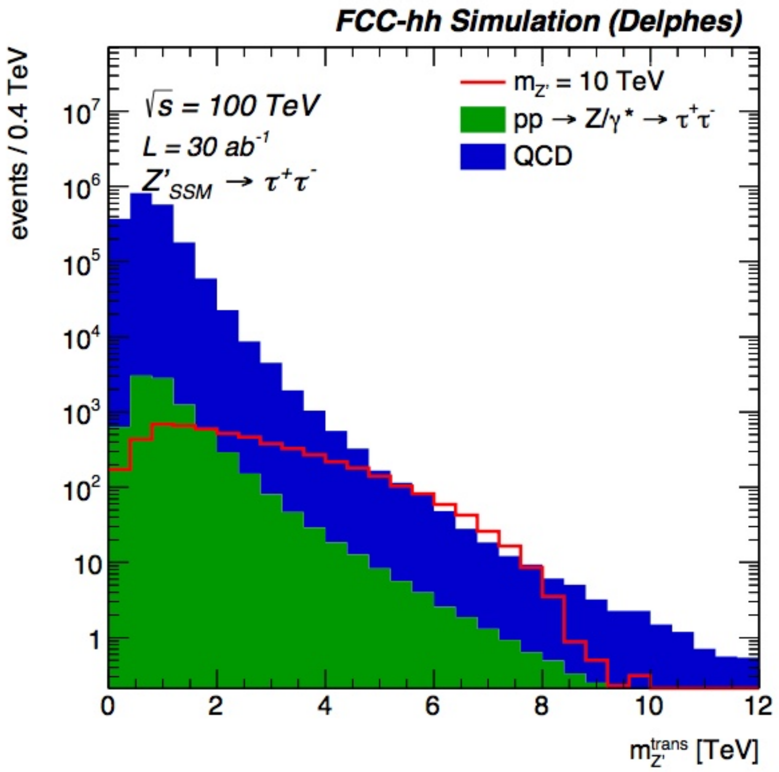
Accurate reconstruction and momentum measurements of p_T = 20 TeV
-> require large lever arm, excellent spatial resolution and precise alignment of the tracking plus muon systems.



Z'->ττ

- Analysis selection (hadronic taus only as most sensitive)
  - $p_T(j1/2) > 1$TeV, $|\eta(j1/2)| < 2.5$
  - At least 2 tau tags

Z' mass [TeV]	$\Delta\phi(\tau_1,\tau_2)$	$\Delta R(\tau_1,\tau_2)$	E_T^{miss}
$4-8$	>2.4	>2.5 and <3.5	>400 GeV
10	>2.4	>2.7 and <4	>300 GeV
$12-14$	>2.6	>2.7 and <4	>300 GeV
$16-18$	>2.7	>2.7 and <4	>300 GeV
>18	>2.8	>3 and <4	>300 GeV

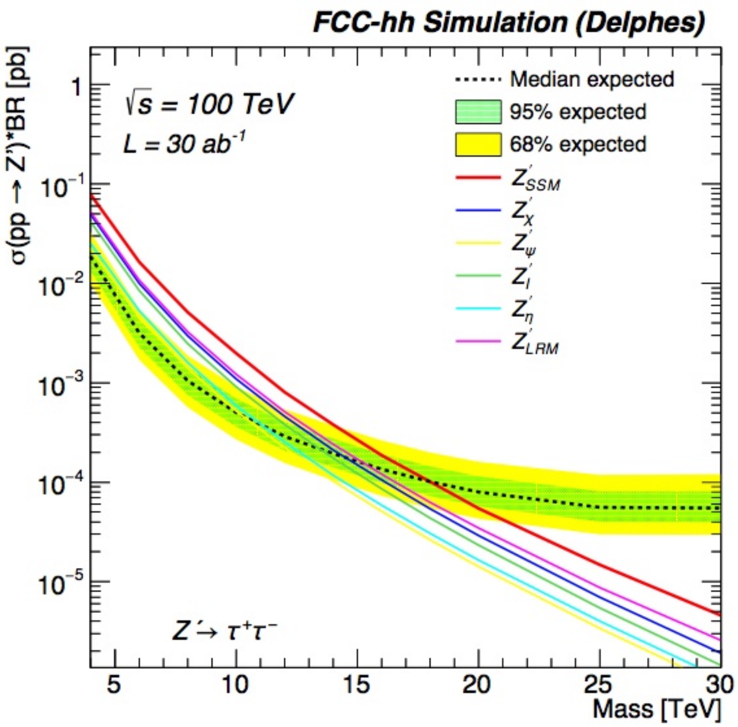


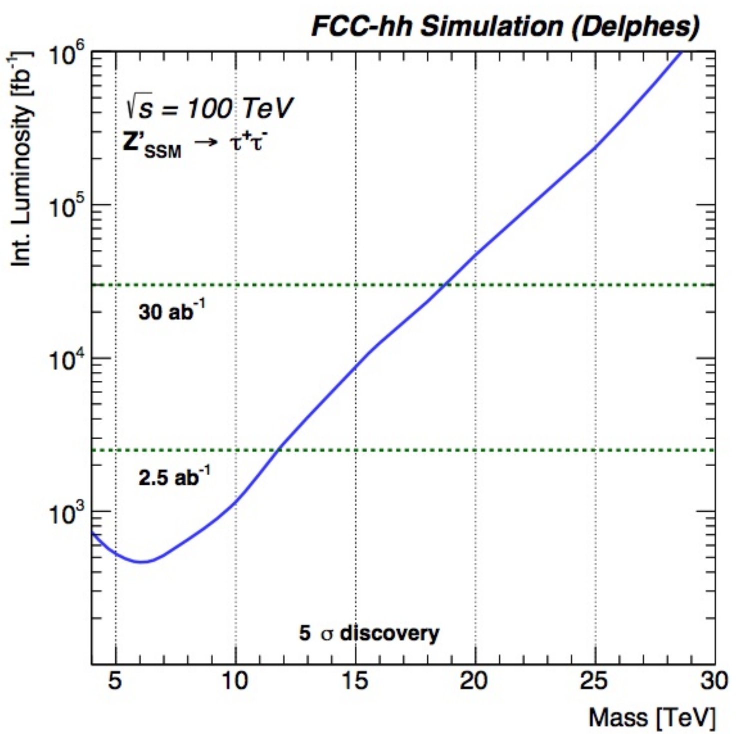
- Uncertainties
  - 50% uncertainty on the Drell-Yann normalization
  - 50% uncertainty on the Di-jet normalization

Limit/significance

<u>5σ discovery for:</u>
- 12TeV after 10 years @ baseline
- 19TeV after full operation 25 years

Challenges: better tau tagging at high p_T

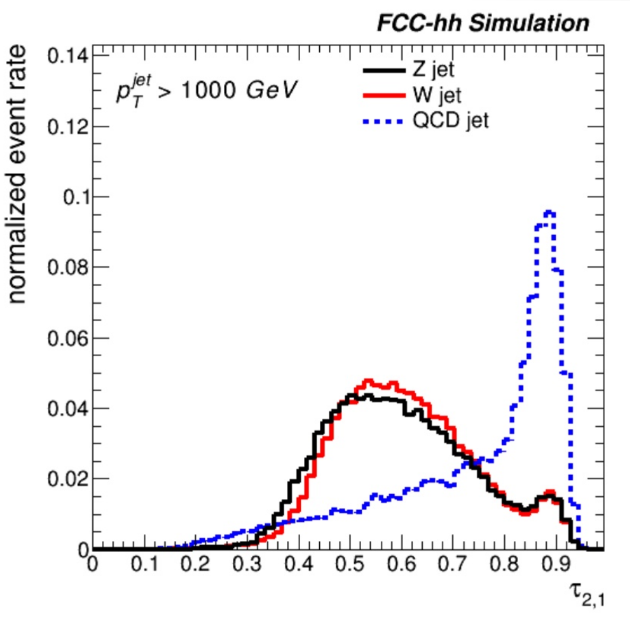




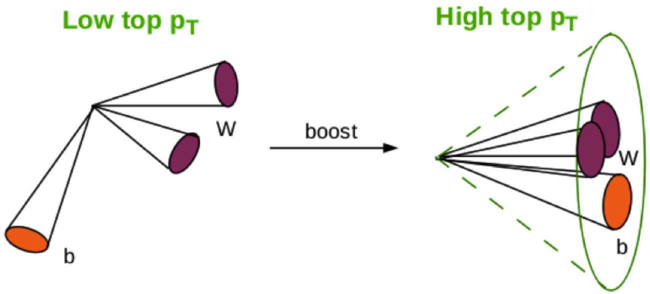
Z’->tt

Z'->ttbar

- Z' model
  - Signal with Pythia8
  - Important benchmark model for detector performance on sub-structure



$\Delta R \cong 2m/p_T$



Top-quark

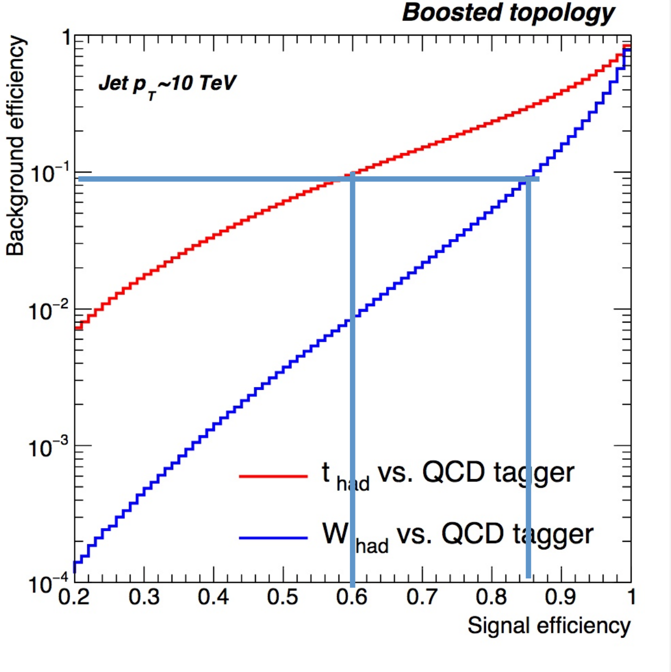
LHC: p_T ~ 1TeV → ΔR=0.5

FCC: p_T ~ 10 TeV → ΔR = 0.05

Multivariate discriminant

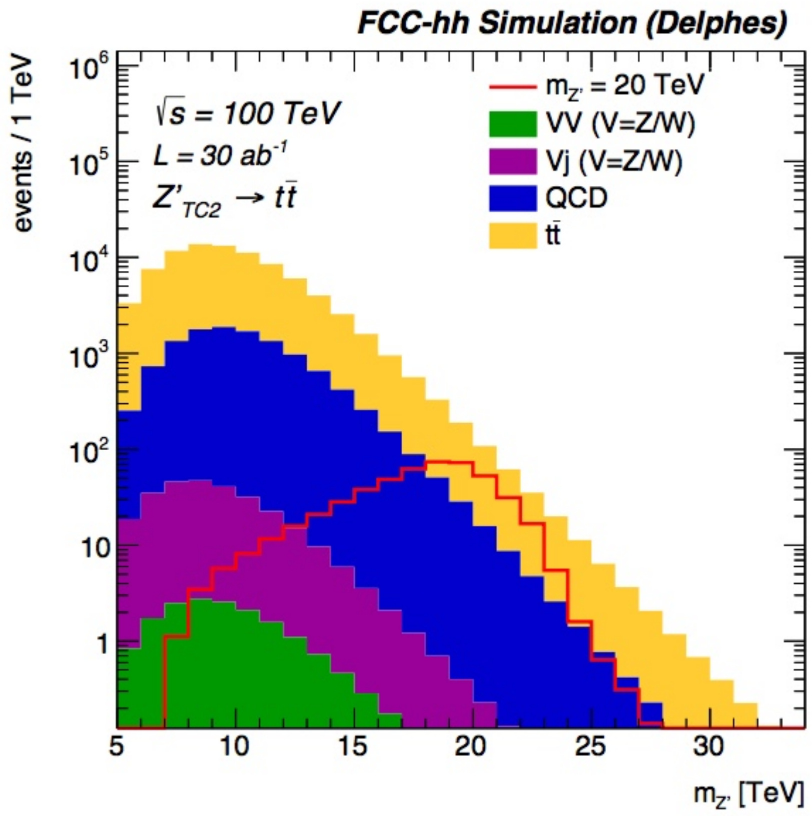
- Developed MVA discriminant to disentangle overwhelming QCD jets from boosted W/tops

W tagger		top tagger	
variable	weight	variable	weight
τ_3 (track jet, R=0.2)	0.12	τ_1 (track jet, R=0.2)	0.21
m_{SD} (track jet, R=0.2)	0.11	m_{SD} (track jet, R=0.2)	0.17
τ_{31} (track jet, R=0.2)	0.10	τ_{31} (track jet, R=0.2)	0.11
$E_F(n=5, \alpha=0.05)$	0.09	τ_2 (track jet, R=0.2)	0.10
$E_F(n=4, \alpha=0.05)$	0.09	τ_3 (track jet, R=0.2)	0.09
$E_F(n=1, \alpha=0.05)$	0.08	m_{SD} (track jet, R=0.8)	0.09
$E_F(n=2, \alpha=0.05)$	0.07	m_{SD} (track jet, R=0.4)	0.09
$E_F(n=3, \alpha=0.05)$	0.06	τ_{32} (track jet, R=0.2)	0.08
τ_{21} (track jet, R=0.2)	0.06	τ_{21} (track jet, R=0.2)	0.06
m_{SD} (track jet, R=0.8)	0.06		
m_{SD} (track jet, R=0.4)	0.06		
τ_1 (track jet, R=0.2)	0.05		
τ_2 (track jet, R=0.2)	0.04		
τ_{32} (track jet, R=0.2)	0.02		



Z'->ttbar

- Z' model
  - Important benchmark model for detector performance
    on sub-structure
- Analysis selection
  - $p_T(j_{1/2})$ >3TeV, $|\eta(j_{1/2})|$ <3
  - Jet1,2 Soft Dropped mass>100GeV
  - Jet1,2 τ_{21}, τ_{32}>0
  - $|\eta_{jet1} - \eta_{jet2}|$<2.4
  - 2 b-tag jets, 2 top jets from MVA discriminant
  - Do not explicitly select leptons,
    but "correct" di-top mass for MET
- Uncertainties
  - 20% uncertainty on the ttbar normalization
    50% on di-jet 40% on Vj and 20% on VV



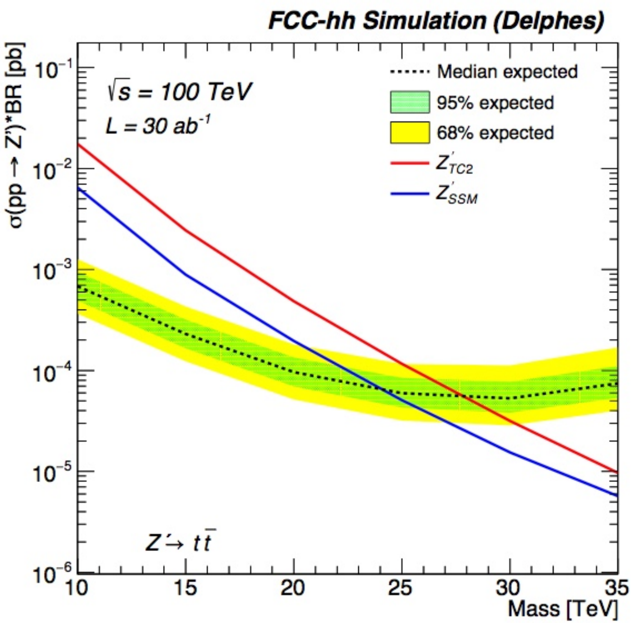
Z'->ttbar

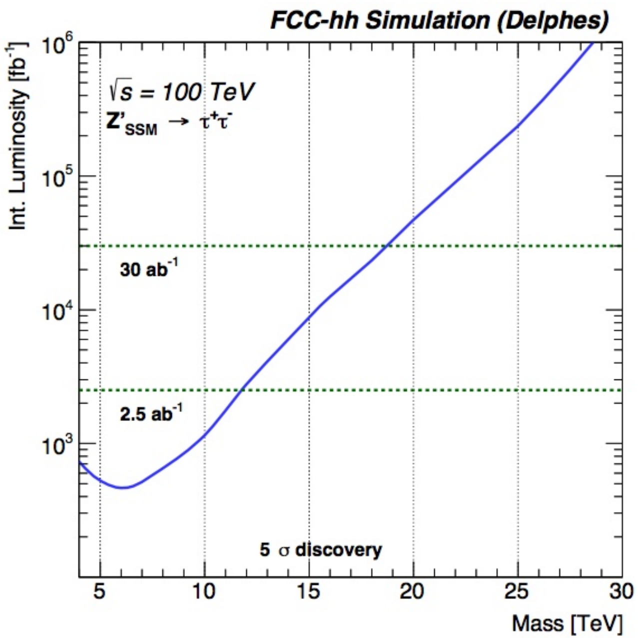
5σ discovery for TC2:
- 17TeV after 10 years @ baseline
- 23TeV after full operation (25y)

5σ discovery for SSM:
- 11TeV after 10 years @ baseline
- 16TeV after full operation (25y)

Challenges: better top tagging from sub-structure, and improve m_{tt} mass resolution

SSM is obviously a benchmark for leptonic decays





Discovery tt degraded

High efficiencies (ε_b > 60%) for corresponding low mis-identification probability ($\varepsilon_{u,d,s}$ < 1%) from light jets have to be achieved up to p_T = 5 TeV.

For example, searches for heavy resonances decaying to hadronic tt pairs heavily rely on efficient b-tagging performance at such energies.

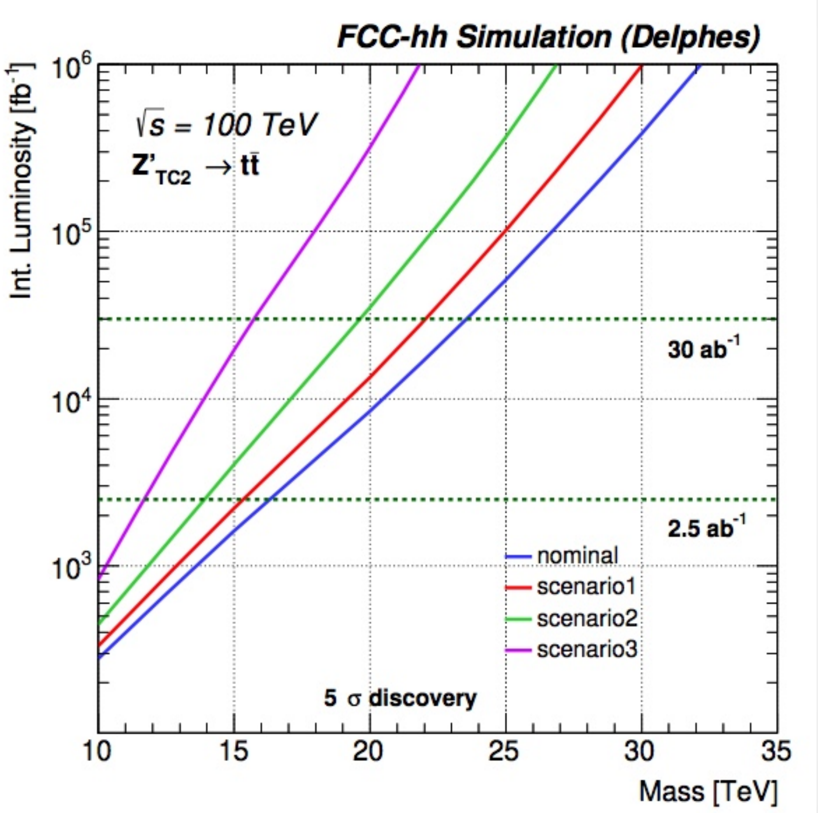
Discovery reach for specific Z′ model assuming several scenarios for b-jet ID at very large p_T are considered

-> Nominal efficiency $(1-p_T/15\text{TeV})*85\%$ (between 500GeV and 15TeV, 0 above 15TeV)

-> scenarios 1,2, 3 correspond to reduction of the slope by a factor 25%, 33% and 50% (random scaling)

As expected the discovery reach strongly depends on the b-tagging performances.

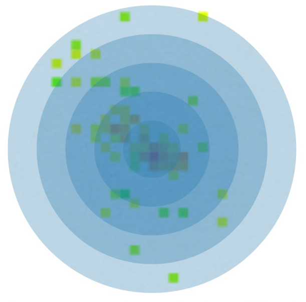
Of course it is not guaranteed that such behavior can be achieved, this needs more detailed full simulation



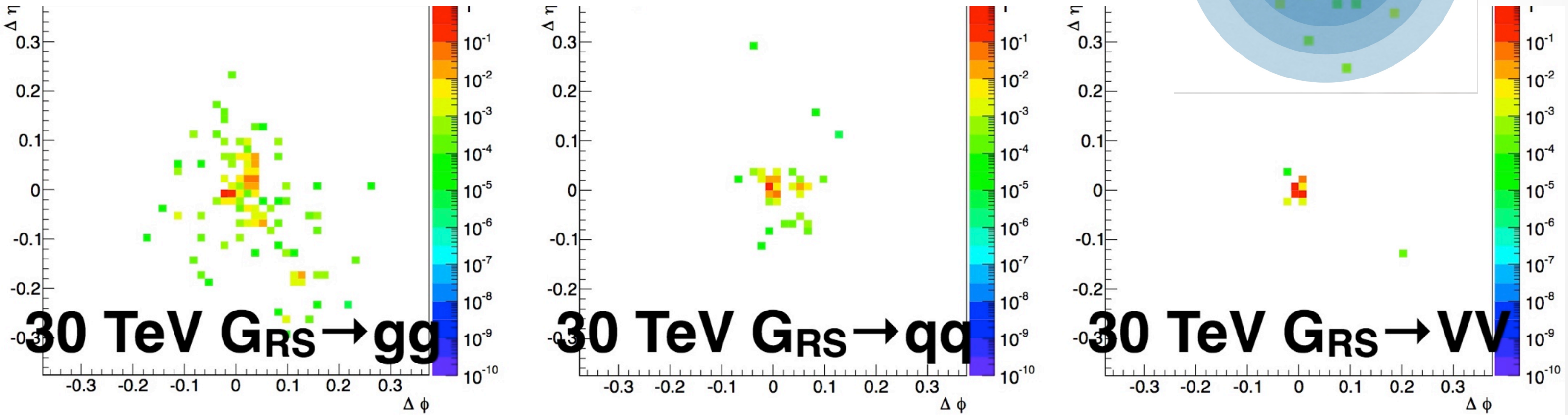
RSG->WW
W->jj

Di-boson resonance (only hadronic)

- Randall-Sundrum Graviton
  - Signal with pythia8
  - Important benchmark model for detector performance on sub-structure
- W/Z bosons
  - LHC: p_T ~ 1TeV →ΔR=0.25
  - FCC: p_T ~ 10 TeV → ΔR = 0.025

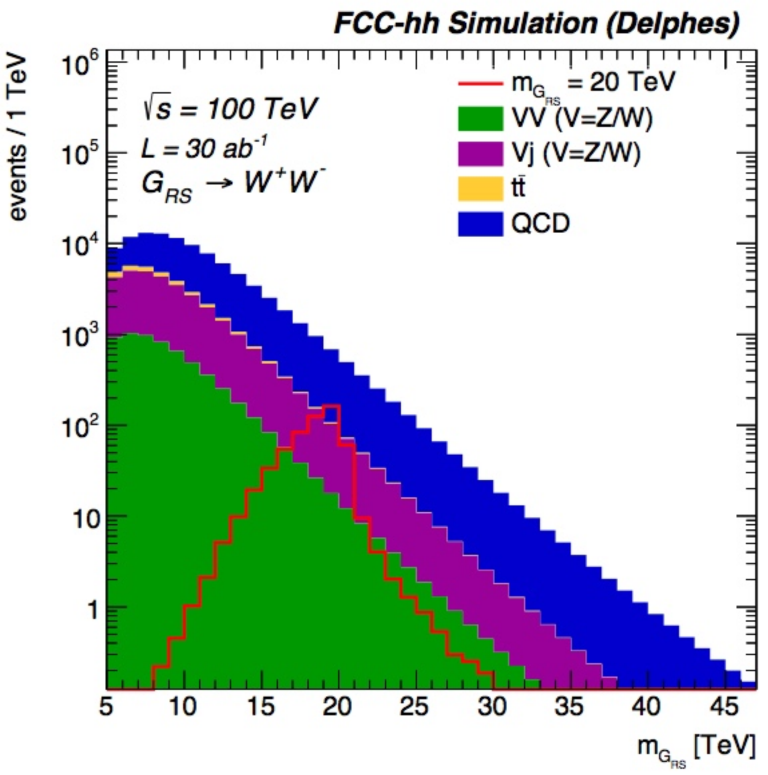


$$\frac{n-1}{5}R \le \Delta R(k,\text{jet}) < \frac{n}{5}R, \quad \text{Flow}_{n,5} = \sum_k \frac{|p_T^k|}{|p_T^{\text{jet}}|}$$



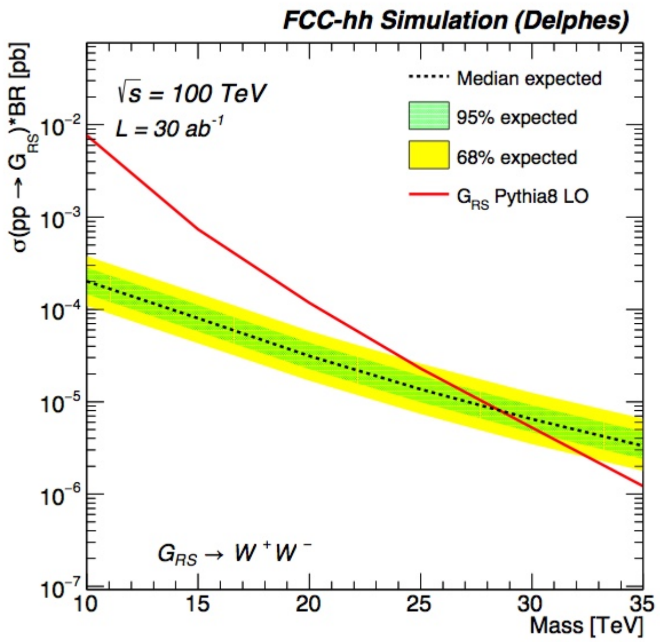
Di-boson resonance (only hadronic)

- Randall-Sundrum Graviton
  - Important benchmark model for detector performance on sub-structure
- Analysis Selection (Fully hadronic)
  - Jet1/2 p_T>3TeV, jet1/2 $|\eta|$ <3
  - J1,2 τ_{21}, τ_{32}>0
  - $|\eta_{jet1} - \eta_{jet2}|$<2.4
  - 2 W jets from MVA discriminant
- Norm uncertainties
  - ttbar 20% QCD 50%, VV 20%, VJ 40%



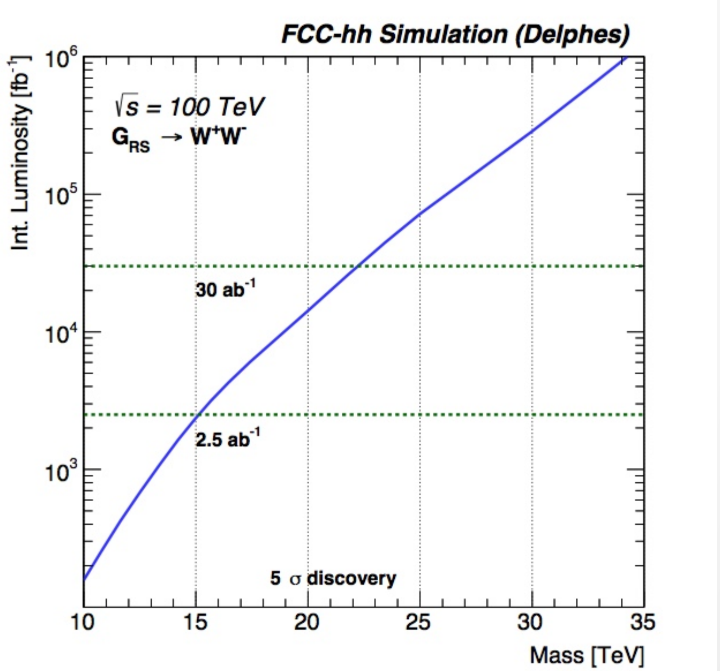
RSG->WW

Challenges: better W tagging from sub-structure, and improve m_{WW} mass resolution



5σ discovery for RSG:

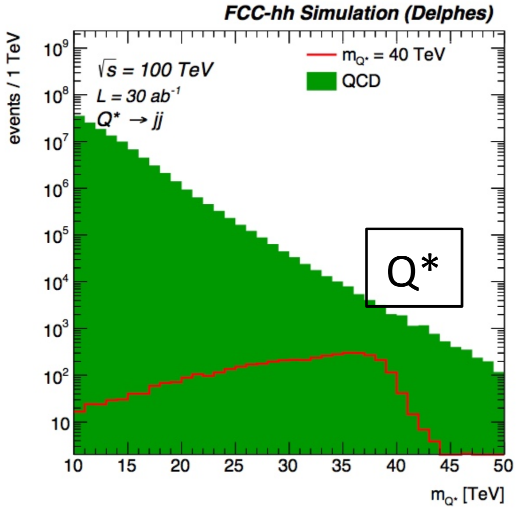
- 10TeV after 1 years (~100fb^{-1})
- 15TeV after 10 years @ baseline
- 22TeV after full operation 25 years

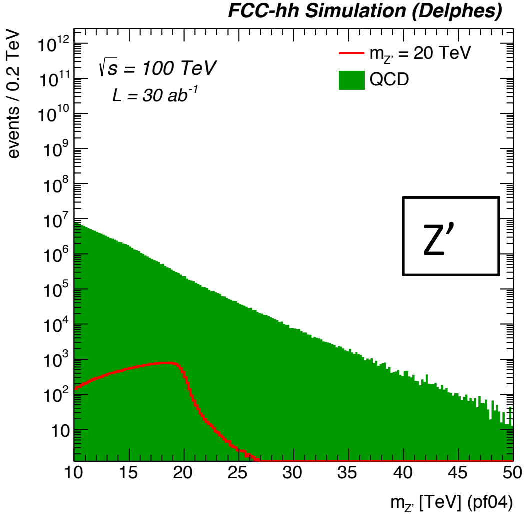


Q*->jj

Q*/Z'->jj

- Q* model
  - Strongly coupled
  - Wide, large cross section
- Z' model
  - Same benchmark as Z' -> leptons
  - Narrow, small cross section
- Analysis selection
  - $p_T(j1)$ and $p_T(j2)>3TeV$
  - $Y^*=|yjet1-yjet2|/2 < 1.5$
- Uncertainties
  - 50% uncertainty on the Di-jet normalization

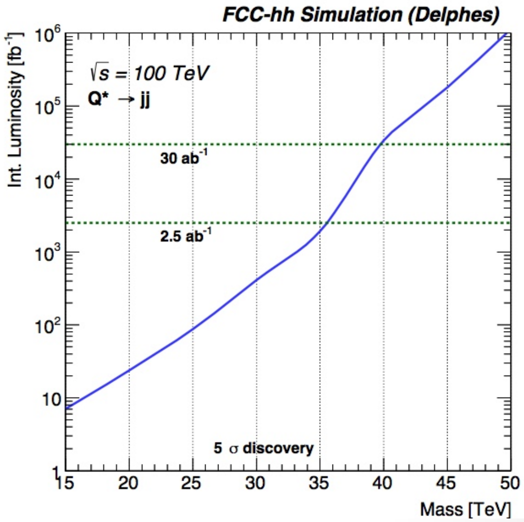




5σ discovery for Q* (wide and strongly coupled):

- 15TeV after 1 day (1fb^{-1})
- 36TeV after 10 years @ baseline
- 40TeV after full operation 25 years

Q*

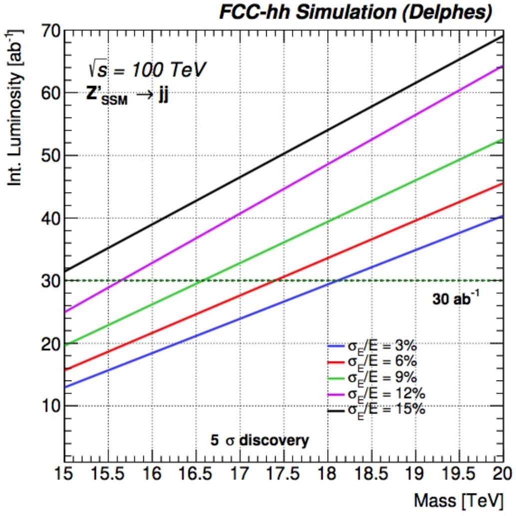


5σ discovery for Z' (narrow and weakly coupled):

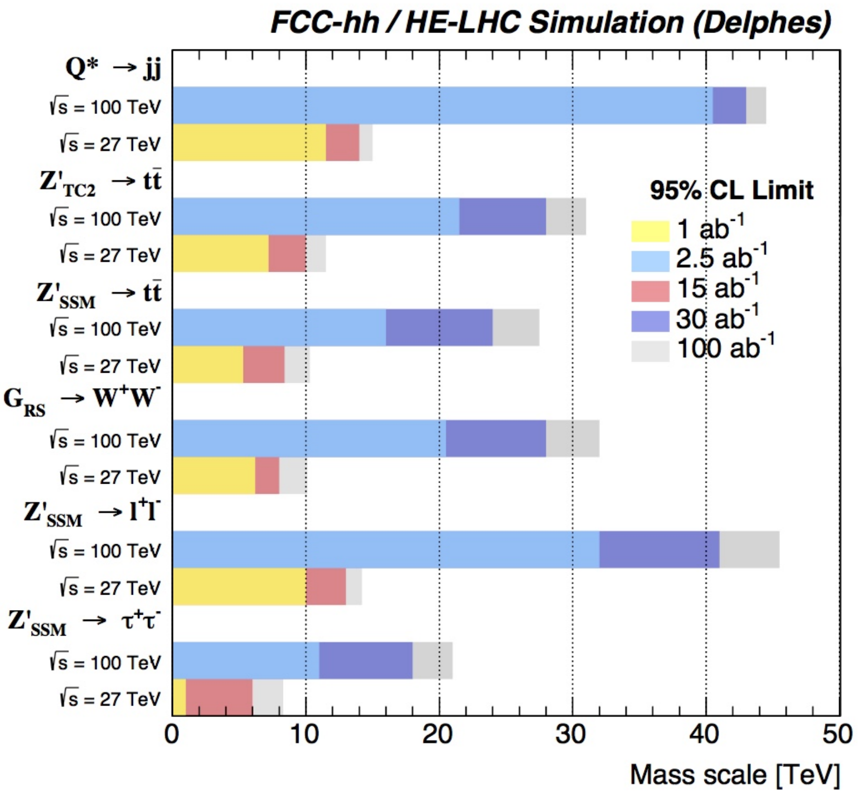
- <15TeV after 10 years @ baseline
- 19TeV after full operation 25 years

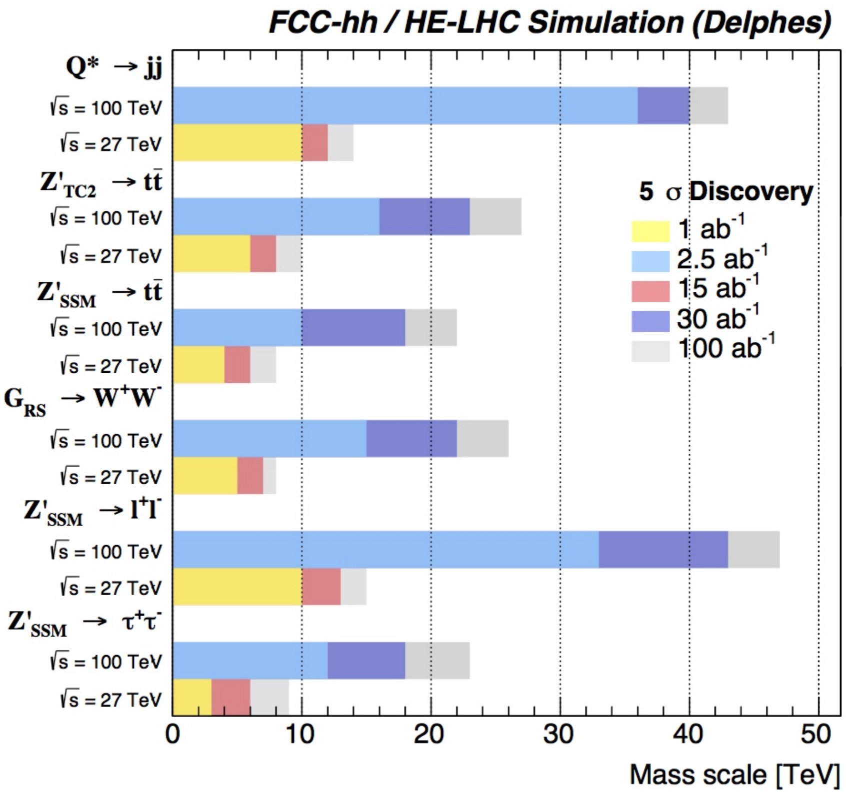
Smearing the mass (increasing the calorimeter constant term) has a large impact on the discovery potential

Z'



Summary at FCC-hh HE-LHC





3. Perspectives for future work

Dilepton resonance

- Z’->e^+e^-
  - Electrons are not an issue at high mass
- Z’->$\mu^+\mu^-$
  - Very high p_T muons could be problematic but this was already studied
  - Could improve the analysis for Z’ flavour anomaly and s-channel leptoquark
- Z’-> $\tau^+\tau^-$
  - Was not fully optimized
  - Could find better discriminant than the transverse mass
  - Could find better ways to discriminate τ versus QCD jets
  - Could include leptonic tau decays
  - Could study tau identification
  - Synergy with heavy higgs?

Hadronically Decaying Resonances

- Z'->tt
  - Improve the top-tagging
  - Include leptonic top decays
  - Study in full simulation b-tagging in a hadronic top decay
- V'->VV (V=Z/W)
  - Improve the boson tagging
  - Only RSG->WW studied could also consider Z-bosons (hadronic W/Z separation for model discrimination)
  - Include leptonic decays
- Q*->qq
  - Study at low mass with ISR?
  - Trigger issues?

To be studied

- W'->tb
  - Interesting for boosted top and very high p_T b-jets (decay well inside the tracker)
  - First simple assessment done (1910.09788), may be repeated with more detailed simulation

- W'->lν
  - Interesting for MET resolution at high p_T

- V'-> VH (V=Z/W/H)
  - Interesting for very high p_T Higgs boson tagging
  - Calorimeter and tracker granularity
  - How to resolve 2 close by very high p_T b-jets

4. Full Simulation

Possible studies

- Granularity for boosted objects
  - For example in 1901.11146 there is a detailed studies of the calorimeter granularity on boosted topologies ID
  - I started within the context of FCC to check in full simulation the performance of the boosted taggers developed for the physics analyses (calorimeter only) to understand where we stand
- High energy jets
  - I started Alberto Ribon from G4 to use a modified physics list with EPOS in order to study the effect of missing interactions at high energies
- Lots of devolvement opportunities for FS work
  - Flavour tagging
  - Pile-up
  - …

5. The FCC-hh framework

https://cds.cern.ch/record/2717892 Also submitted as LoI
https://www.snowmass21.org/docs/files/summaries/EF/SNOWMASS21-EF-TOPIC0-007.pdf

CERN-FCC-PHYS-2020-0005
12 May 2020

A framework and goals for FCC-hh physics studies at Snowmass 2021

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Abstract

We summarize the key results obtained by physics studies carried out for the FCC-hh Conceptual Design Report, documenting the existing tools and software framework that were developed. Indications are provided for further work, on physics performance and simulation software development, which could be a target for Snowmass 2021 studies of a pp collider at 100 TeV. The primary goal of this note is to inform about, and document, the existing resources, to encourage coordination and collaboration building on the work already done.

How to get information/contribute

- In each section of the document people are listed as contacts
  - Please do not hesitate to get in touch
  - Expertise should be kept, transferred, improved
    - There is no need to reinvent the wheel again
- Ongoing developments
  - Delphes plugin in Key4Hep is being developed
  - For FCC studies we will move to it, and this could also be a nice opportunity for SnowMass people

List of analyses

- Each directory represents a dedicated analysis that runs on a common set of samples
  - Common shared modules
  - Easy for anyone to take over an analysis and run it

- Dijet_reso
- RSGraviton_ww
- W_top_vs_QCD_tagger
- Zprime_ll
- Zprime_mumu_flav_ano
- Zprime_tautau
- Zprime_tt
- h2l2v
- h4l
- haa
- hh_boosted
- hhbbaa
- hhbbaa_cms
- hmumu
- hza
- ttV_test
- tth_4l
- tth_boosted
- tth_mumu
- tttt
- vbs
- vbs_ww

6. Outlook

Outlook

- Heavy resonances are one of the key benchmark for detector design
  - High p_T muons -> magnet strength
  - Boosted objects -> Calorimeter and tracker granularity
  - Very high energetic jets -> Calorimeter containment
- For FCC-hh
  - Showed that the detector requirements to achieve the needed performances are with reach
  - Of course more detailed studies, especially to validate the achieved performances in full simulation/reconstruction are welcome
- Future work
  - Include leptonic decay channels
  - Improve boosted object tagging (very relevant for VLQ topologies that were not very much studied at 100TeV)
  - Improve high p_T b-jet tagging

Backup

Expectation from hadron future collider

Guaranteed deliverables

- Study Higgs and top-quark properties and exploration of EWSB phenomena with unmatchable precision and sensitivity

Exploration potential (New machines are build to make discoveries!)

- Mass reach enhanced by factor √s/14TeV (5-7 at 100TeV)
  - Statistics enhanced by several orders of magnitude for possible BSM seen at HL-LHC
- Benefit from both direct (large Q^2) and indirect precision probes

Could provide firm answers to questions like

- Is the SM dynamics all there at the TeV scale?
- Is there a TeV-Scale solution the hierarchy problem?
- Is DM a thermal WIMPS?
- Was the cosmological EW phase transition 1st order? Cross-over?
- Could baryogenesis have taken place during EW phase transition?

Frontier Hadron Colliders on the Market

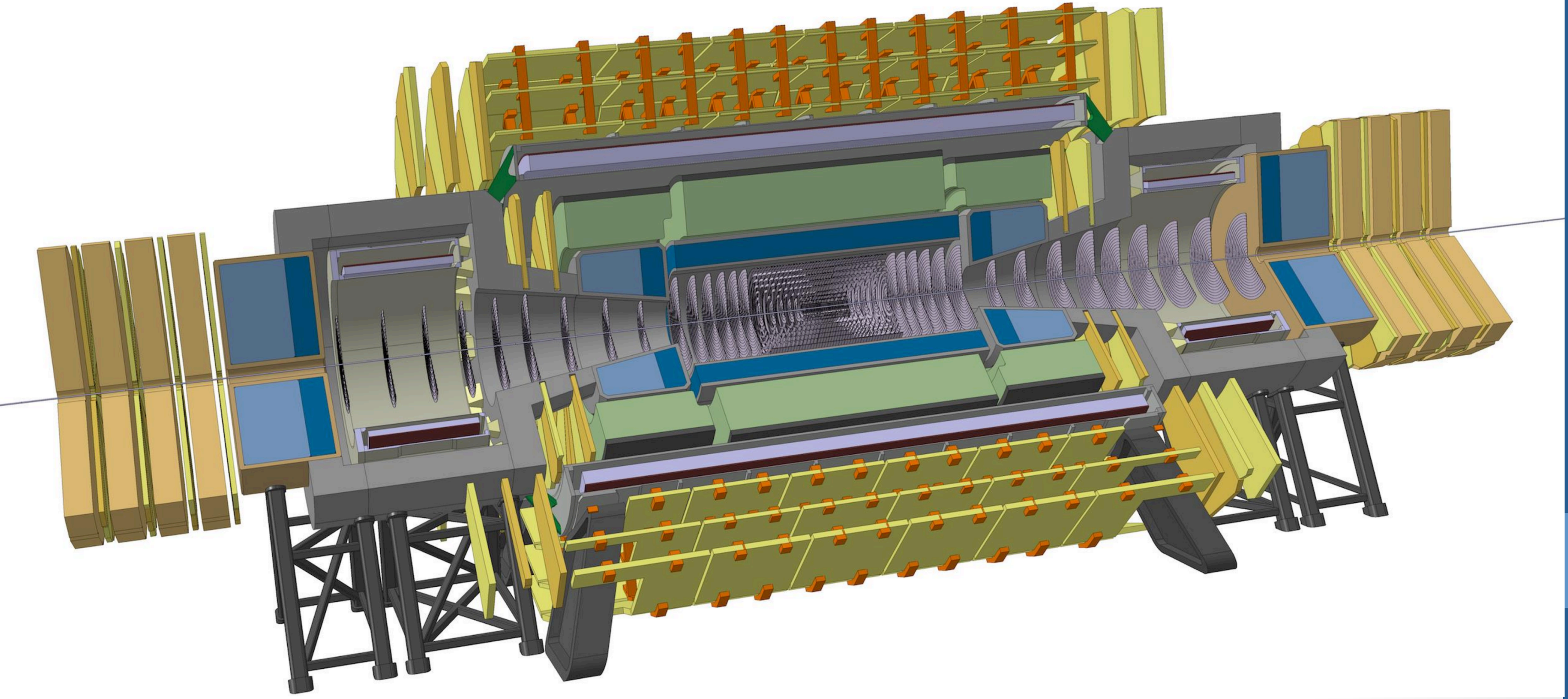
- FCC-hh (100TeV in 100km)
  - Studied in details for the CDRs and input to European Strategy
  - Integrated program with FCC-ee coming first

- HE-LHC (FCC-hh magnets in LHC -> 27TeV)
  - Also studied for European Strategy
  - Unlikely: physics outcome versus price/machine complexity is bad

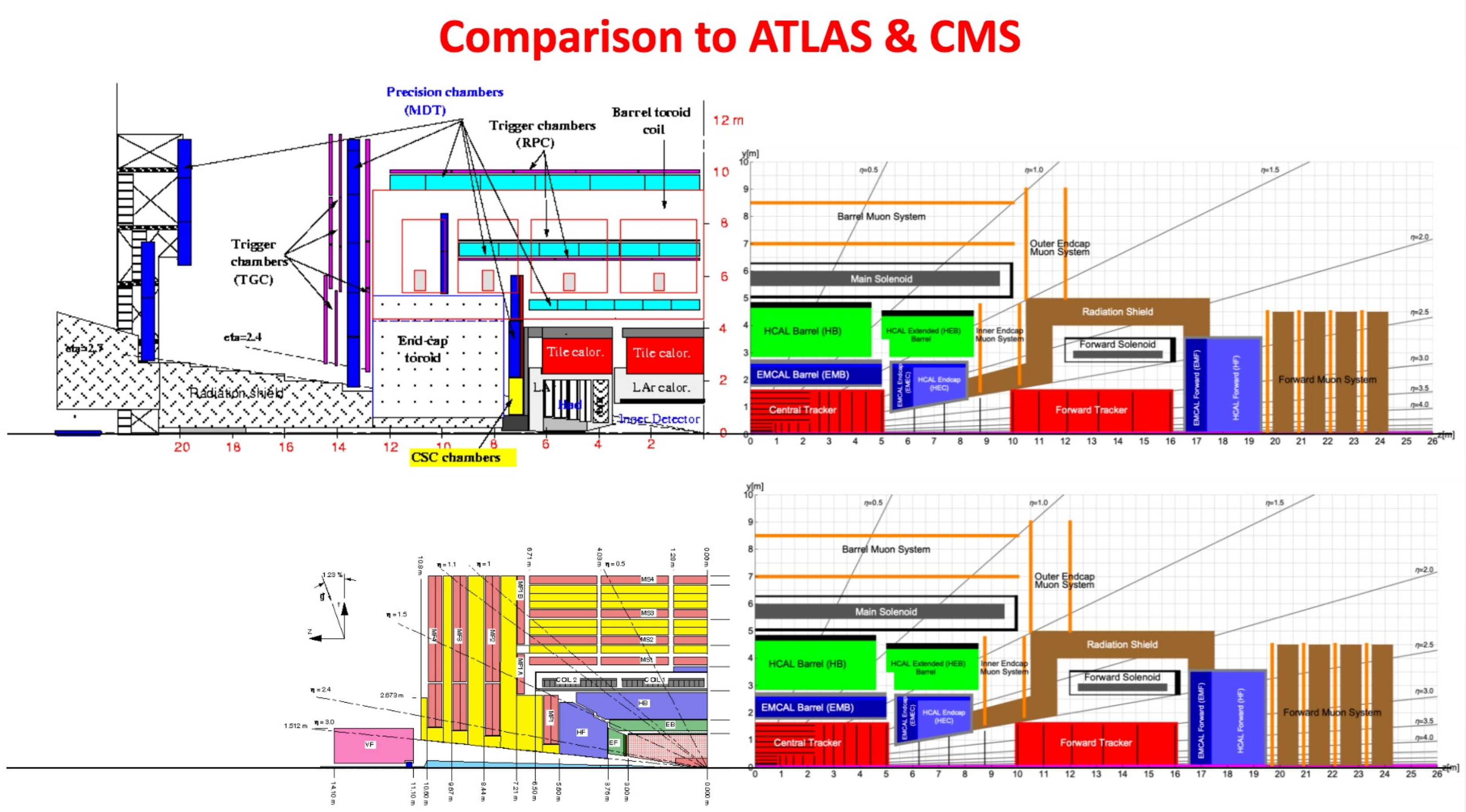
- LE-FCC (LHC magnets in 100km -> 37.5TeV)
  - Option raised during the European Strategy
  - Large degradation (2-3) wrt FCC-hh, minor improvements wrt HE-LHC

- SppC (after CepC, 80-100TeV)
  - Not much studies done so far

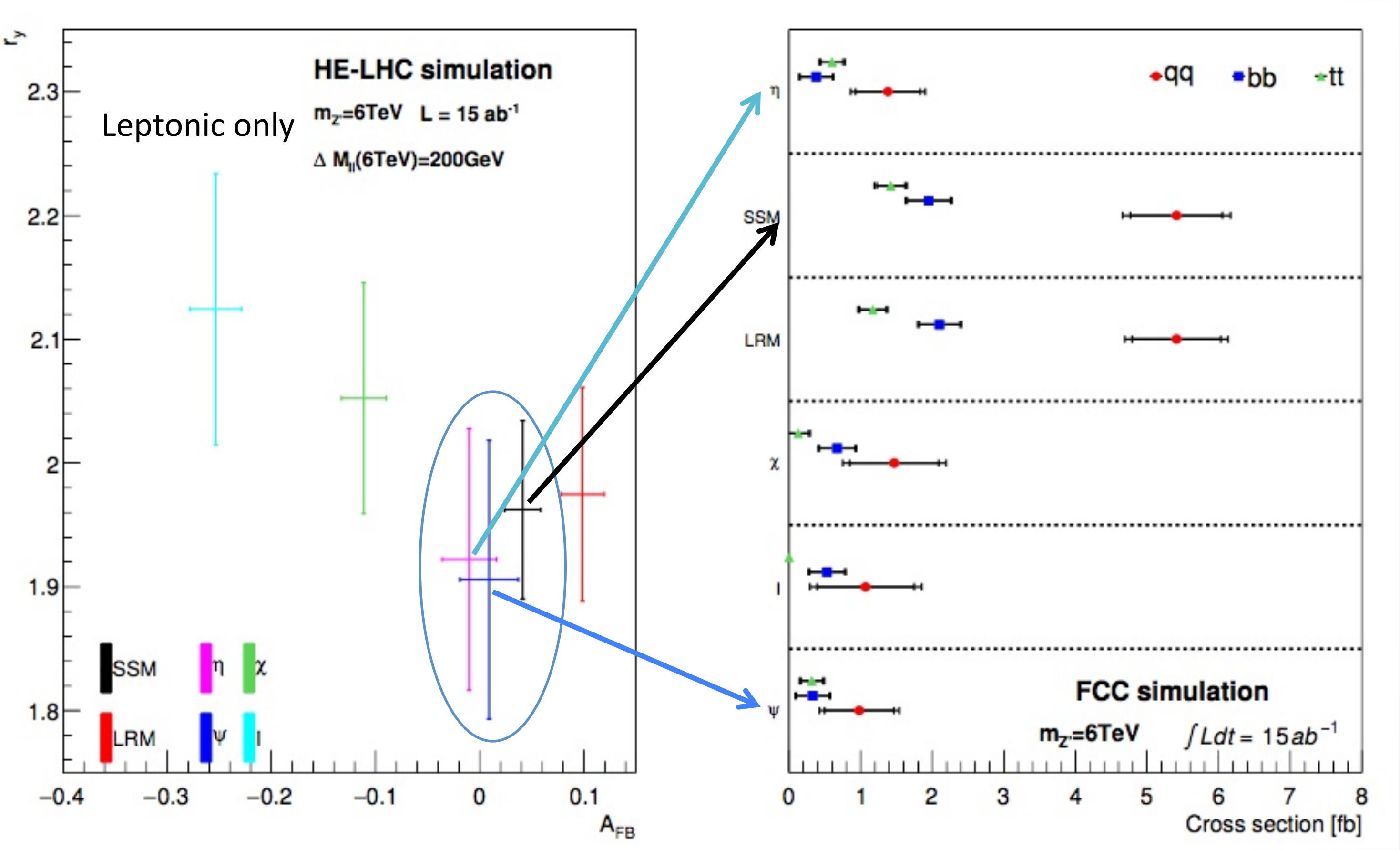
FCC-hh detector



FCC-hh detector



Discrimination of Z' models within LHC reach



Summary

- Di-lepton($ee/\mu\mu$)
  - Background free analysis
  - Discovery reach ~42TeV with full dataset for SSM model
- $Z'\to\tau\tau$ (hadronic taus)
  - More complex final state
  - Discovery reach ~19TeV with full dataset
  - Need better high p_T tau tagging techniques
- Ttbar
  - Discovery reach up to 23TeV
  - better top tagging from sub-structure, and improve m_{tt} mass resolution
- Di-boson
  - Discovery reach up to 22TeV
  - better W tagging from sub-structure, and improve m_{WW} mass resolution
- Di-jet
  - Reach up to 40TeV
  - Calorimeter containment for best resolution

Technicalities

- Signals:
  - Mainly produced with Pythia8
  - MG5 in some cases (interpretations)
  - No k-factor assumed
- Backgrounds :
  - with MG5 LO
  - k-factor of 2 assumed
- Software
  - Using FCC software with detector parameterization
  - When setting limits, use full shape and profile likelihood ratio

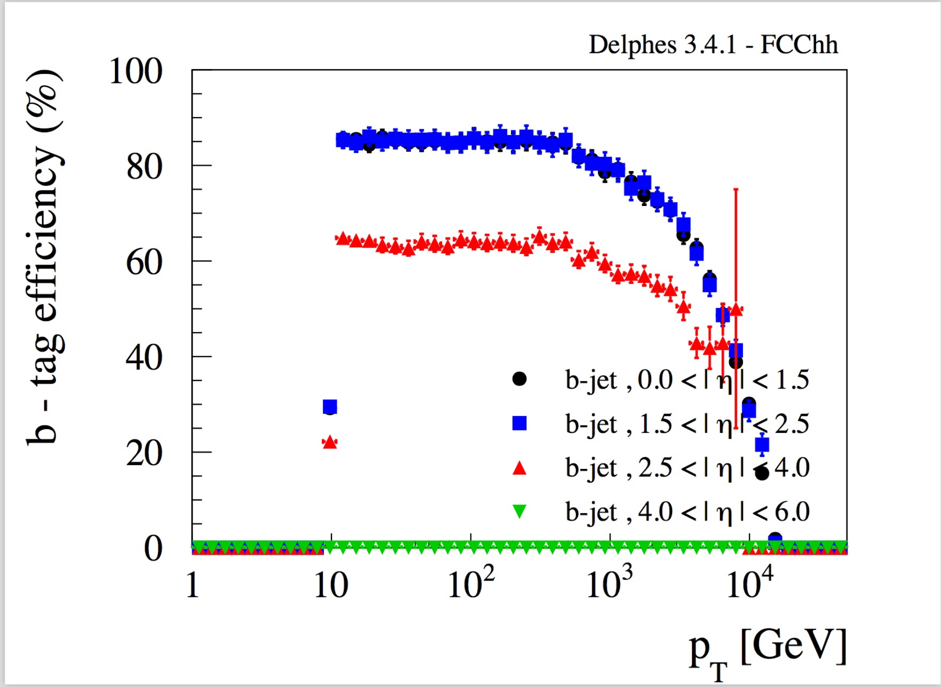
Sample	Cut (TeV)	Statistic (10^6)
Di-electron	$p_T(e)>5$	10
Di-muon	$p_T(\mu)>5$	10
Di-tau	$p_T(\tau)>2.5$	10
Di-tau	$2.5>p_T(\tau)>1$	5
Di-jet	$p_T(j)>2.5$	50
Di-jet	$2.5>p_T(j)>1$	30
Di-boson	$p_T(V)>2.5$	15
V+jets	$m_{Vj}>5$	10
Top pair	$p_T(t)>2.5$	10

FCC-hh Analysis Framework

- GridPack producer
  - Makes MG5_aMC@NLO GridPacks
- LHE Producer
  - Produce LHE files on LSF/condor queues from GP or standalone MG5
  - About a 2 billion events produced
  - http://fcc-physics-events.web.cern.ch/fcc-physics-events/LHEevents.php
- FCCSW
  - Runs Pythia8 parton shower+hadronisation and Delphes with FCC detector
- Analysis preselection and high level variable definitions
  - Python framework produces flat ROOT trees
- Analysis Final selection and plots
  - Python framework for optimising analysis cut flows and producing
- Limit setting
  - Atlas inspired tool for limits and significance
- More info in my talk at the FCC software session Thursday afternoon

B-tagging

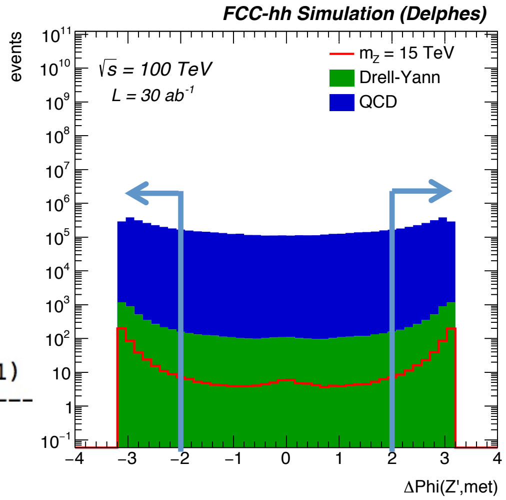
- High p_T b-tagging
  - Very displaced vertices
  - After the 1st 2nd or even 3rd layer of the pixel detector
  - Used for this top pair resonance search
- Estimate
  - Need a first realistic estimate of how b-tagging will perform
  - Using results from full simulation study without tracks (hit multiplicity jump)
  - See Estel Perez talk at detector session

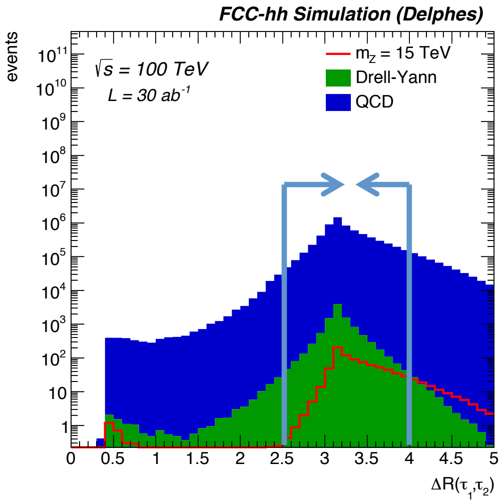


Z'->ττ

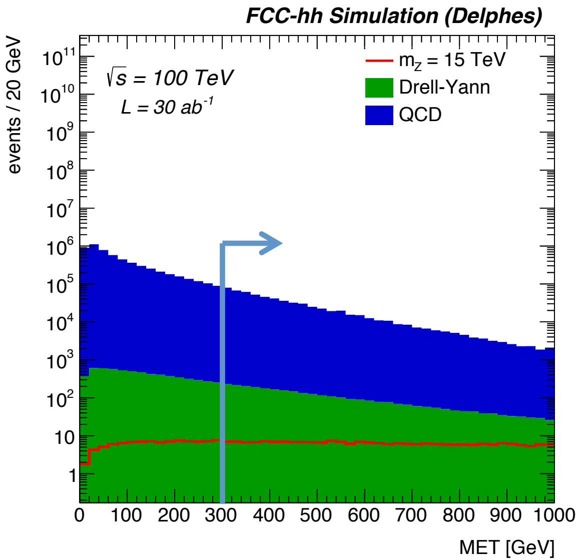
$p_T(j1/2) > 1$TeV, $|\eta(j1/2)| < 2.5$

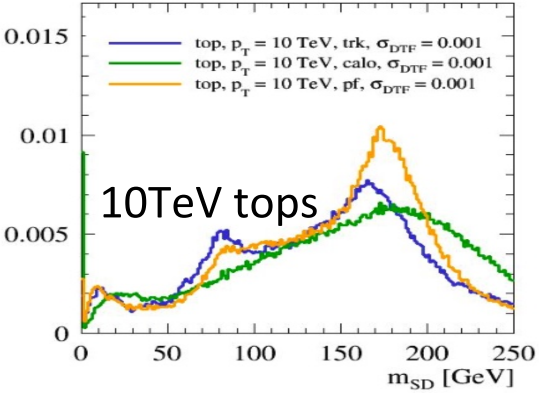
process	yield (30.0 ab-1)
m_{Z} = 15 TeV	888.9
Drell-Yann	10237.8
QCD	7116045.3

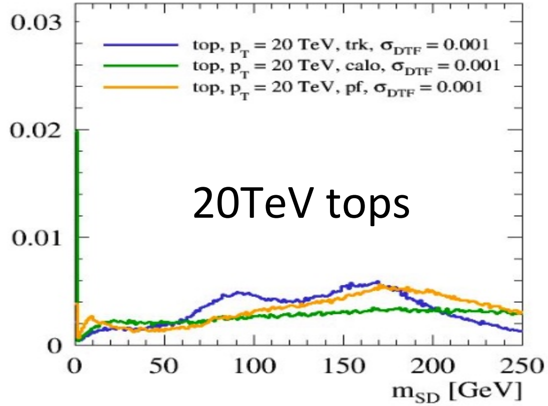


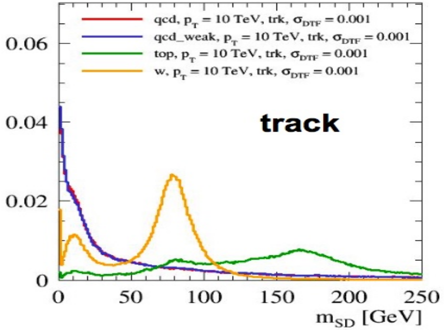


process	yield (30.0 ab-1)
m_{Z} = 15 TeV	781.0
Drell-Yann	10083.6
QCD	6426072.2

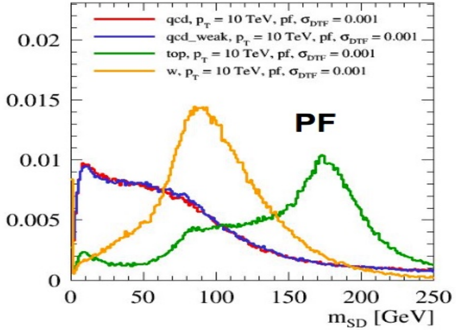








10TeV objects



- Track jets seems to be more robust and better understood at high p_T
- Use those at high p_T corrected by p-flow jet p_T when using substructure

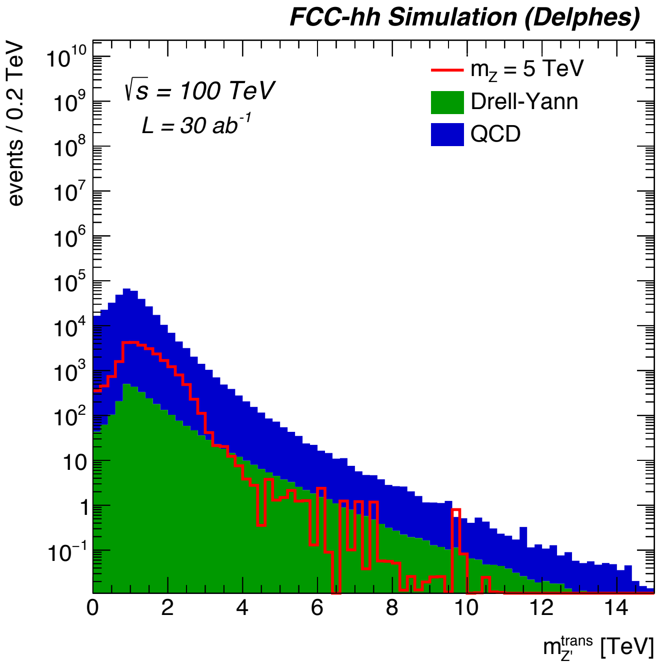
Z'->ττ

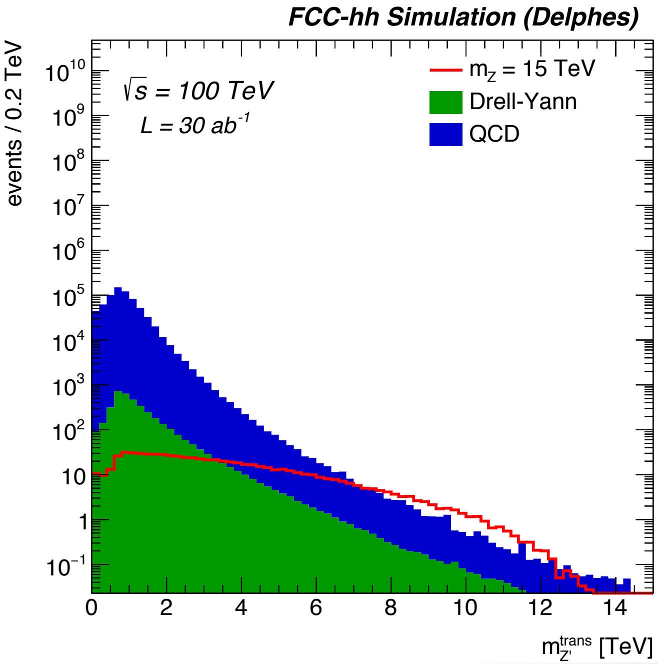
Z' = τ1+τ2 (4 vectors)

m_T = sqrt(2*p_T(Z')*MET*(1 – cos(Δϕ($\phi_{Z'}$ - ϕ_{MET}))))

process	yield (30.0 ab-1)
m_{Z} = 5 TeV	25345.8
Drell-Yann	2715.5
QCD	361221.2

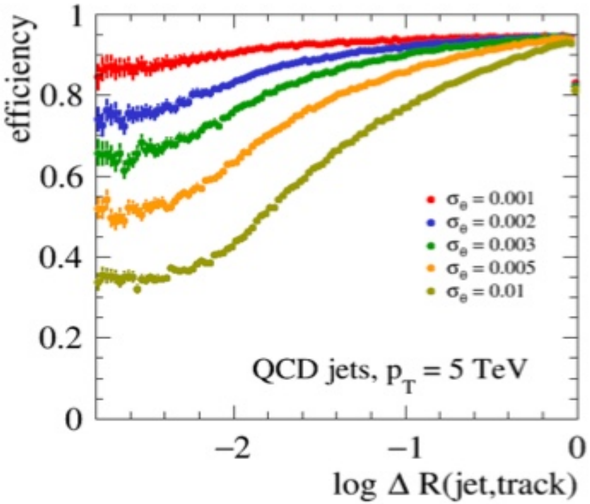
process	yield (30.0 ab-1)
m_{Z} = 15 TeV	686.2
Drell-Yann	3769.5
QCD	695272.8

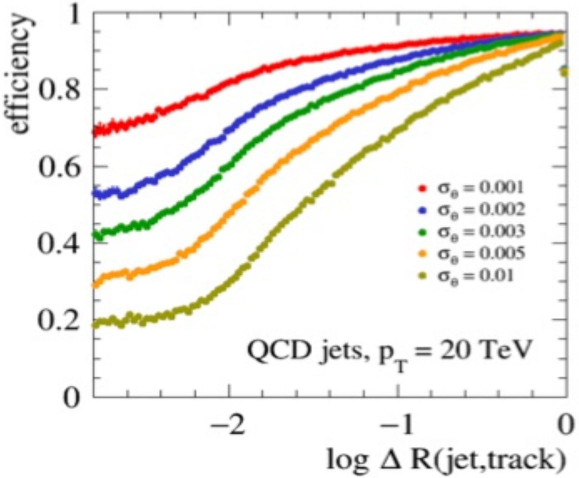




Tracking in dense env.

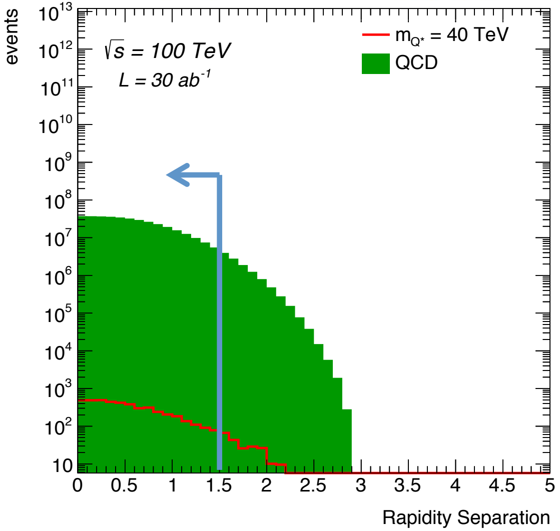
- Tracker granularity
  - Defined in (η x ϕ)
  - Worst case scenario
    - pitch size in the first pixel layer: reso = (2-3)*10um/(0.025) ~ 0.001
- Inefficiency
  - when two or more tracks hit same pixel
  - keep only highest p_T track
  - Arbitrary and probably conservative, considering that this is only first pixel layer
- Conservative value
  - 0.001 used for FCC studies

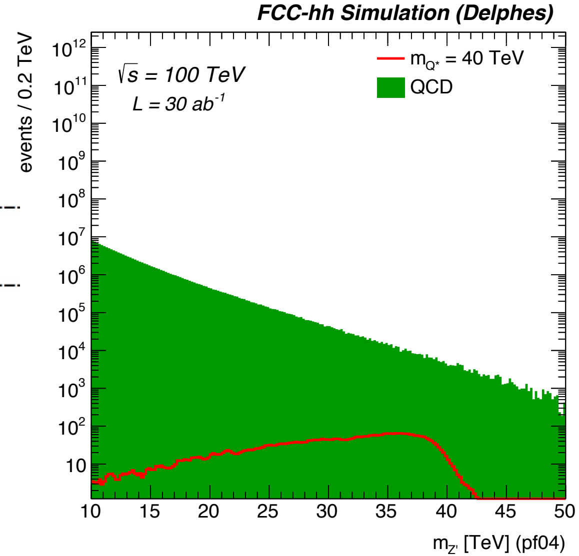


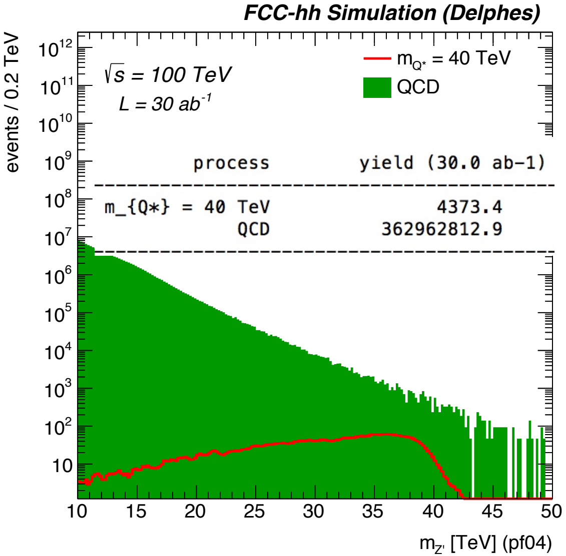


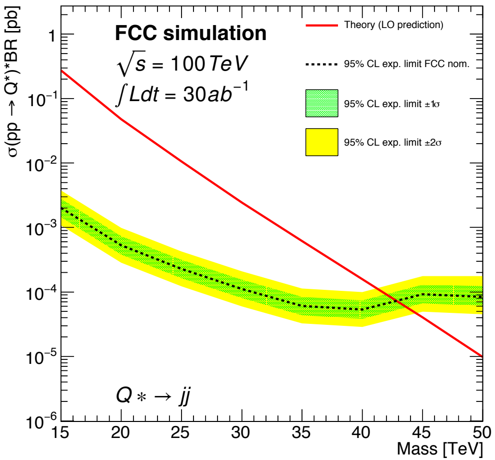
Q*->jj

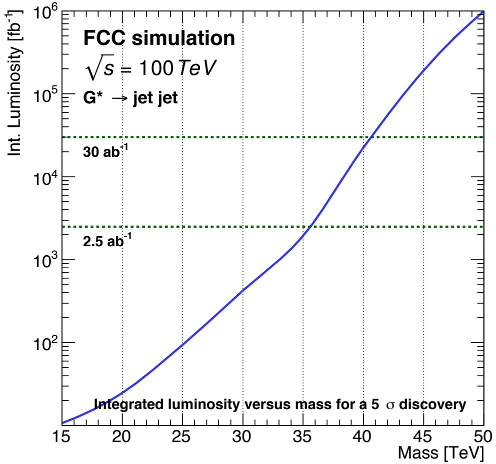
process	yield (30.0 ab-1)
m_{Q*} = 40 TeV	4588.9
QCD	374687859.9









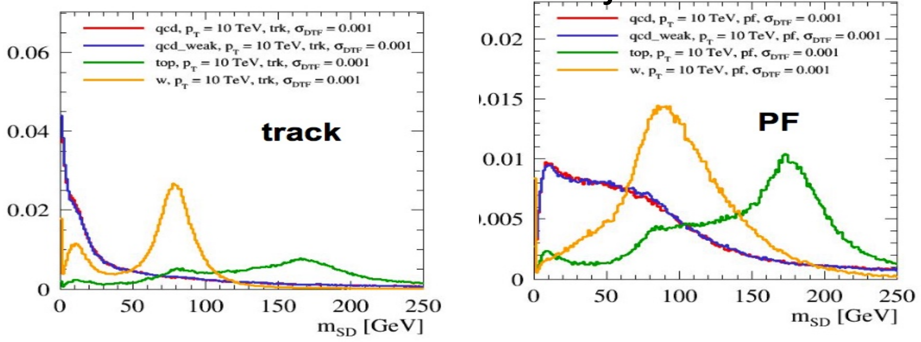


5σ discovery for Q*:

- 15TeV after 1 day ($1fb^{-1}$)
- 36TeV after 10 years @ baseline
- 40TeV after full operation 25 years

Boosted objects

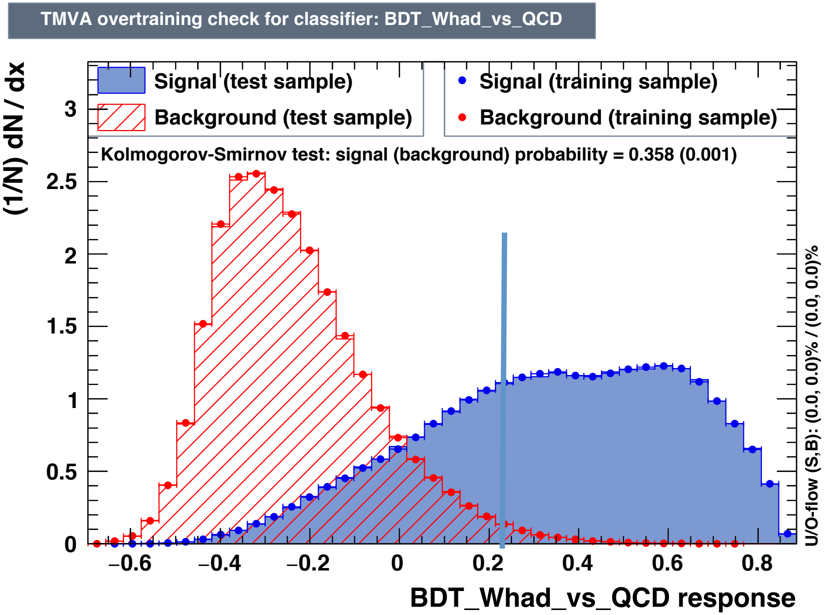
10TeV objects

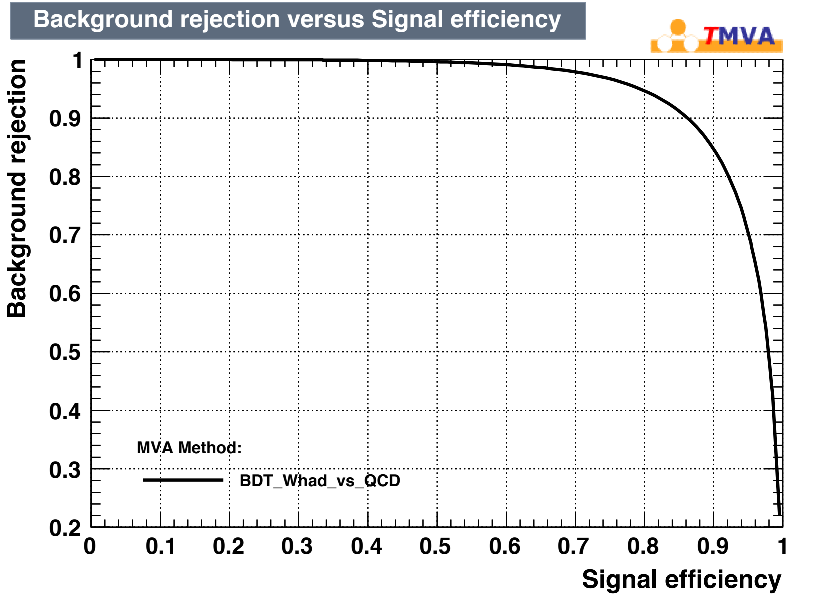


- What is:
  - Optimal jet collection
  - Minimal track angular resolution?
- Assessed using :
  - QCD, QCD+weak shower, W and Top jets
  - GenJets, CaloJets, Particle Flow Jets, Track Jets with 2-5-10-20 TeV
- Outcome:
  - Use track jets for sub-structure corrected to pf jets
  - More information in this talk here
- Performance of reconstructing such boosted objects is being further investigated in full simulation for the report
- Track jets seems to be more robust and better understood at high p_T
- Use those at high p_T corrected by p-flow jet p_T when using substructure

W versus QCD jet tagger

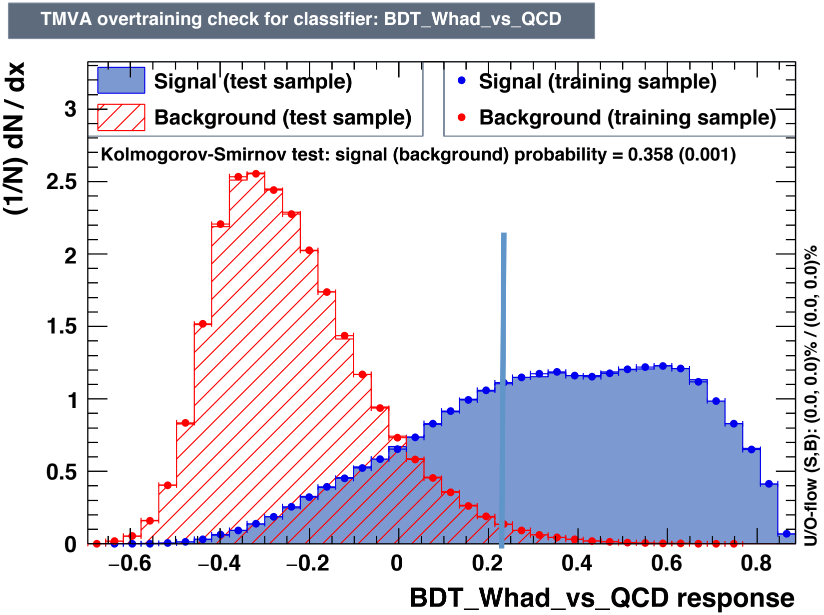
Variables used
Flow 1,2,3,4,5/5
Soft dropped mass
τ32, τ21, τ1/2/3





W versus QCD jet tagger

Variables used
Flow 1,2,3,4,5/5
Soft dropped mass
τ32, τ21, τ1/2/3



Top vs QCD
W versus QCD